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A novel BEV concept based on fixed and swappable li-ion battery packs

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***Abstract*—In this paper a novel battery electric vehicle (BEV) concept based on a small fixed and a big swappable li-ion battery pack is proposed in order to achieve: longer range, lower initial purchase price and lower energy consumption at short ranges. For short ranges the BEV is only powered by the relatively small fixed battery pack, without the large swappable battery pack. In this way the mass of the vehicle is reduced and therefore the energy consumed per unit distance is improved. For higher ranges the BEV is powered by both battery packs. This concept allows the introduction of subscription-based ownership models to distribute the cost of the large battery pack over the vehicle lifetime. A methodology is proposed for the analysis and evaluation of the proposed concept in comparison with a direct owned non swappable single pack BEV, proving that significant improvements on city fuel economy (up to 20 %) and economic benefits are achievable under several scenarios. These results encourage further study of battery swapping service plans and energy management strategies.**

I. Introduction

Electro mobility, which covers Hybrid, Plug-in Hybrid, and Battery Electric Vehicles (HEVs, PHEVs, and BEVs), is considered as the future in automotive transportation. It provides environmental, economic and energy security benefits, maximizes vehicle and driving efficiency, and it integrates easily with Smart Grid technologies. In fact, the global light duty EV market is expected to grow from 2.7 million vehicle sales in 2014 to 6.4 million in 2023 [1].

However, the electric automotive industry is still facing many challenges, most of them related with the Energy Storage System (ESS). In that regard, Li-ion Batteries (LIBs) are nowadays the preferred solution for the ESS in BEVs and PHEVs, due to their superior performance in terms of specific energy and energy density (up to 240 Wh/kg and 640Wh/L) [1]–[6]. Also, Li-ion are expected to be adopted in near future for HEVs and stop-start applications, which are nowadays markets dominated by nickel-based and lead acid batteries respectively [1]–[6].

Despite of that, BEVs in comparison with gasoline-powered vehicles still have too high initial purchase prices, due to costly LIBs. They present other well-known commercial barriers, such as limited ranges, limited battery lifetime, limited tolerance of the battery for thermal or electrical abuse, poor battery performance at low temperatures, long re-fuelling or charging time at domestic power levels or lack of charging infrastructure [1]–[6].

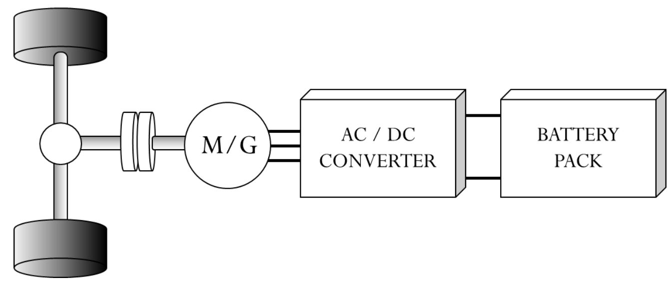


Fig. 1: Diagram of a BEV designed with a conventional single LIB topology.

During many years, due to these limitations, automotive industry designed and produced small urban BEVs with relatively short ranges. But in recent years the BEV market has undergone a change of paradigm: Tesla achieved commercial success with Model S, a luxury sedan which offers an appealing design, long range (up to 270 mi with a 85 kWh LIB pack), high performance, on-board charger (10 kW) and a growing network of superchargers[1]. Furthermore, it should be noted that Model S is designed to allow fast (sub-one minute) battery swapping, even though stations are not available yet, which is considered a key feature by consumers according to recent studies [7]. It follows that high cost may not represent an absolute barrier as soon as those other requirements are fulfilled. In fact, other brands moved into the same direction, like Mercedes-Benz with the new B-Class Electric Drive or Toyota with the new RAV4 EV, including on-board chargers and the largest LIB packs nowadays in the BEV market after Model S (36 and 42 kWh respectively). However, these proposals are in luxury segment and therefore their overall market penetration is still limited by cost (>40 kUS$).

In this paper, the energy consumption performance and cost-effectiveness of a novel BEV concept based on a fixed and swappable LIB packs (see Fig. 2) are evaluated, in comparison

[1]"Tesla Motors' Success Gives Electric Car Market a Charge," *National Geographic*, May 21, 2013. Available: http://news.nationalgeographic.com/news/energy/2013/05/130522-tesla-motors-success [Retrieved 15.12.2014]

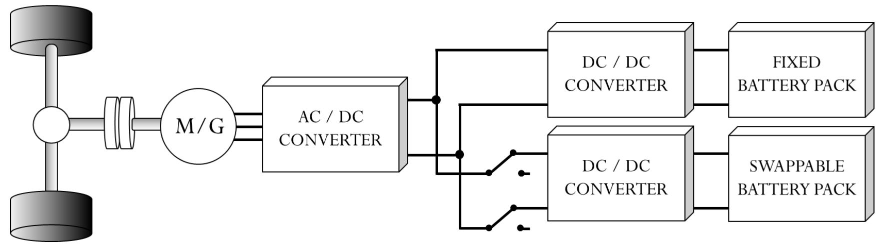


Fig. 2: Diagram of a novel BEV designed with a fixed and swappable LIB topology.

with direct owned non-swappable single pack BEVs (Fig. 1). For short ranges the BEV is only powered by the small battery pack, without the large swappable battery pack. In this way the mass of the vehicle is reduced and therefore the energy consumed per unit distance is lower. For higher ranges the vehicle is powered by both battery packs. This concept allows the introduction of subscription-based ownership models to distribute the cost of the large battery pack over the vehicle lifetime. Besides of that, further capabilities can be provided by using this dual design: hybridization of different ESSs, diagnosis tools or charging from battery-to-battery in motion.

It should be noted that the proposed BEV concept is analysed based on an energetic approach, and therefore designing issues related with the power train, suspension, braking system, battery packaging, chassis aerodynamics, among other aspects are not considered in this paper.

The paper is organized as follows. In Section II, mathematical models of the LIB pack and the BEV from wheel-to-battery are described. In Section III, vehicle specifications are presented in order to define a virtual platform which will be used to evaluate the proposed BEV concept. In Section IV, the energy consumption of the virtual BEV designed with a fixed and a swappable LIB battery is evaluated in simulations and performance results are compared side-by-side with other BEVs equipped with a single LIB pack. In Section V the impact of the novel BEV concept on battery lifetime is estimated. In Section VI a simplified economic analysis is conducted in order to estimate the cost-effectiveness of the novel concept proposed. Finally, Section VII gives the conclusions.

II. Vehicle Model

A. Longitudinal Vehicle Dynamics

The power and energy requirements for an EV are dependent, not only on its characteristics (total vehicle mass, rolling resistance, aerodynamic and energy losses from the powertrain), but also the driving cycle to which the vehicle will be subjected. According to that, the driving cycle's characteristics (speed profile $V(t)$, road angle $\alpha(t)$ and cycle duration T_s) are deterministic.

From the driving cycle and vehicle characteristics information, applying at the same time Newton's law, the vehicle's demanded power can be obtained as follows:

TABLE I: MAIN VEHICLE PARAMETERS

AAUDI			
Variable	Symbol	Value	Unit
Vehicle's mass w/o drivetrain	m_V	1200	kg
Traction system + inverters	m_T	185	kg
Fixed battery pack mass	m_F	196	kg
Swappable battery pack mass	m_S	589	kg
No. cells in series	n_s	108	-
No. of strings [fixed pack]	n_{pf}	1	-
No. of strings [swappable pack]	n_{ps}	3	-
Aerodynamic drag coefficient	C_d	0.3	-
Air density	ρ_a	1.2	kg/m^3
Gravity	g	9.8	m/s^2
Frontal area	A_f	2.7072	m^2
Wheel radius	r	0.32	m
Gearbox ratio	G	8.06	-
Rolling friction coefficient	f_r	0.013	-
Motor losses	X	$[1275, 2.8, 0, \ldots$ $0.1, 0.1, 0]$	-
Transmission efficiency	η_{Tr}	0.98	-
DCDC converter efficiency	η_{DC}	0.95	-
Electric Motor nominal power	P_{EM}^{max}	216	kW
Auxiliary loads	P_{aux}	0.5	kW

$$P_{out}(t) = V(t)\left(\frac{1}{2}\rho_a C_d A_f V(t)^2\right) + M\left(gf_r cos(\alpha(t)) + gsin(\alpha(t) + \frac{dV(t)}{dt}\right)V(t) \quad (1)$$

where $M = m_V + m_T + m_F + \gamma m_S$, m_V is the vehicle mass without the ESS and traction system, m_T is the mass of the traction system, m_F the mass of the fixed ESS, m_S is the mass of the swappable pack (SP) and g is the gravity acceleration constant. γ is a binary variable which is 1 when the vehicle possess the total energy pack. The first term of the equation is the power demanded by the aerodynamic drag, and the second one depends on the rolling, grading and inertial (respectively) resistance forces. The vehicle's characteristics can be found in Table I.

The delivered power by the ESS must take into account not only the vehicle power demanded, but also the power losses in the powertrain, such as braking losses P_{brk}, transmission P_l^{TR}, electric motor P_l^{EM}, DC/DC converters P_l^{DC}, as well auxiliary loads P_{aux}. As a result, the ESS requested power is given by:

$$P_T = P_{out} + P_{brk} + P_l^{DC} + P_l^{EM} + P_l^{TR} + P_{aux} \quad (2)$$

The losses caused by the transmission efficiency η_{TR}, which

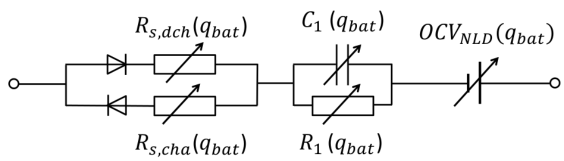


Fig. 3: Non-linear Dynamic Model

is assumed to be constant, are represented by:

$$P_l^{TR}(t) = |P_{out}(t) + P_{brk}(t)|(1 - \eta_{TR}). \quad (3)$$

In its turn, the motor and inverter power losses are approximated by the following fit function:

$$\begin{aligned} P_l^{EM}(t) &= X^T\varphi(T(t),\omega(t)),\ \omega(t) = \frac{G}{r}V(t) && \text{(4a)} \\ \varphi(T,\omega) &= [1\ \ |\omega|\ \ |T|\ \ |T\omega|\ \ T^2\ \ \omega^2] && \text{(4b)} \\ \omega(t)T(t) &= P_{out}(t) + P_l^{TR}(t) + P_{brk}(t) && \text{(4c)} \end{aligned}$$

where T is the motor torque, ω the motor speed, G the reduction ratio between the motor and the wheel, r the wheel radius and X the parameters representing the losses of the model. The considered DC/DC converters were also assumed to present a constant efficiency η_{DC} and therefore:

$$P_l^{DC}(t) = |P_{out}(t) + P_{brk}(t) + P_l^{TR}(t) + P_l^{EM}(t)|\,(1 - \eta_{DC}) \quad (5)$$

B. Battery model

Equivalent Circuit Model: An aggregated battery pack Equivalent Circuit Model (ECM) is considered, based on a non-linear dynamic single cell ECM, see Fig. 3, over a restricted operating window (5-95 % of state of charge (SoC)), without taking into account cell-to-cell variation. A non-linear dynamic model is proposed instead of a liner or non-linear static model in order to make a more accurate estimation of power losses in the battery [8]. The ECM is mathematically characterized as:

$$\begin{aligned} v(t) &= OCV(q(t)) - \Delta v(t) && \text{(6a)} \\ \dot{q}(t) &= -\frac{1}{\overline{Q}}i(t) && \text{(6b)} \end{aligned}$$

where v is the output voltage of the cell, OCV the cell's open-circuit voltage, and Δv the voltage drop in the cell's internal impedance. The SoC is given by q, the maximum charge of the cell by $\overline{Q}$, and the cell's current by $i(\in \mathbb{R})$. Normally, the current, the SoC and the terminal voltage of the cell are constrained by physical limits, which are presented in Table II for the selected cells.

The non-linear dynamic model proposed takes into account SoC-related nonlinearities in the OCV and in the internal resistance, and also first-order dynamics. These nonlinearities are approximated using piecewise linear (PWL) functions. In order to formulate them, let us divide the q range in N_p sub-intervals, $[\underline{q}_k, \overline{q}_k]$, $k \in [1, N_p]$ where $\underline{q}_k$ and $\overline{q}_k$ are the interval

TABLE II: BATTERY PARAMETERS [per cell]

Kokam SLPB 120216216			
Variable	Symbol	Value	Unit
Pouch Cell Mass	$m_{PC,bat}$	1.2	kg
Total Cell Mass	m_{bat}	1.83	kg
Nominal voltage	v_{bat}	3.7	V
Nominal capacity	$\overline{Q}_{bat}$	53	A.h
Initial capacity	$q_{bat}(0)$	0.95	-
SoC limits	$[q_{bat}^{min}, q_{bat}^{max}]$	[0.05,0.95]	-
Current limits	$[i_{bat}^{min}, i_{bat}^{max}]$	[-106,265]	A
Voltage limits	$[v_{bat}^{min}, v_{bat}^{max}]$	[2.7,4.2]	V

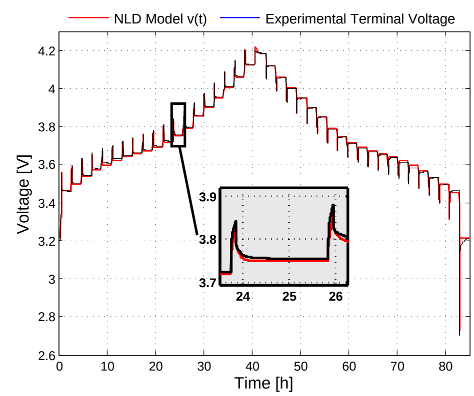


Fig. 4: Experimental terminal voltage versus non-linear dynamic model.

limits.

$$\begin{aligned} OCV(t) &= \sum_{k=1}^{N_p}(u_{0k} + u_{1k}q(t))B(k, q(t)) && \text{(7)} \\ \Delta v(t) &= R_s(q(t))i(t) + \Delta v_c(t) && \text{(8)} \\ \frac{d\Delta v_c(t)}{dt} &= \frac{1}{C_1(q(t))}\left(i(t) - \frac{\Delta v_c(t)}{R_1(q(t))}\right) && \text{(9)} \end{aligned}$$

where u_{0k} and u_{1k} are parameters and $B(k, q)$ is an indicator function that returns 1 if $q \in [\underline{q}_k, \overline{q}_k]$ and 0 otherwise. The same way, variables $R_s(q(t))$, $C_1(q(t))$ and $R_1(q(t))$ are approximated by PWL functions.

Finally, taking account the presented model the demanded pack power during the driving cycle is obtained as follows:

$$P_T(t) = n_s(n_{pf} + \gamma n_{ps})v(t)i(t) \quad (10)$$

where n_s is the number of cells in series, n_{pf} and n_{ps} are the number of strings in parallel for the fixed and swappable packs, respectively. Therefore, the energy consumption of the energy pack can be determined by

$$E_T = n_s(n_{pf} + \gamma n_{ps})\int_0^{T_s} OCV(q(t))i(t)dt. \quad (11)$$

Parametric Identification: The parametrization of the battery model was based on capacity check and step response tests conducted on an uncycled Kokam SPLB 120216216 Li-ion pouch cell, which main characteristics are described in Table II. All tests were conducted at 0.5C (26.5 A) and 25°C.

First of all a full charge and discharge cycle was conducted in order to estimate charging and discharging capacity. Using this information, the battery tester was programmed to fully charge and discharge the cell in consecutive steps of 5 % SoC, considering a 2 h relaxation period between pulses. Thus the OCV vs SoC charging and discharging characteristics are obtained, see Fig. 4.

Since an insignificant hysteresis effect is observed, the average OCV vs SoC characteristic is considered for non-linear fitting. Then, using the same experimental data, the charging and discharging resistances are calculated for every 5 % SoC step conducting a non-linear fitting.

III. Vehicle Specifications

A. Virtual Platform

As part of the FHEEL-project a team at Aalborg University developed a concept car, used as test station for EV related components and technologies. An AWD 4.2 liter gasoline engine Audi A8 Quattro car was converted into a BEV, so called AAUDI [9] (Fig. 5).

This vehicle is used as a virtual platform to evaluate the novel BEV concept proposed in this paper, due to its suitable characteristics: luxury sedan, good aerodynamics, lightweight due to the aluminium body and potentially enough room and load capacity for the battery packs and the electric drivetrain. This means that parameters from the AAUDI are taken as a reference in this paper for assessing the virtual vehicle dynamics in simulations, e.g. vehicle's mass without drivetrain, aerodynamic drag coefficient, frontal area or wheel radius (Table I).

B. Battery Pack

During the FHEEL-project [9], a new high-efficiency drive system was developed [10], including also the battery system. An air cooled modular battery pack made up of Kokam SLPB 120216216 53Ah Li-ion pouch cells was designed, built and installed in the former engine compartment (Fig. 5).

As a result a custom-made 38 kW battery pack made up of 192 cells was developed, achieving a battery pack specific energy of 107 Wh/kg. This reference figure is also taken into account to estimate the mass of the proposed fixed and swappable battery packs in the simulations. Ratings of Li-Ion battery packs and cells employed in current BEVs are compared with our proposal in Table III. Cell's information comes from [11] and pack's information from publicly available sources, such as specialized media and manufacturer's data.

In this case it has been considered a total battery pack energy of 85 kWh, deliberately chosen equal to Tesla Model S for fair comparison. One-fourth of the capacity (21 kWh) is located in the fixed pack (FP) and three-fourths (64 kWh) in the swappable pack (SP). Hence, the smallest pack consists of 108 Kokam cells connected in series, while the largest one is made up 3 of these strings connected in parallel.

Although other options could be considered, this energy distribution was selected for two reasons. Firstly, in this way the nominal operating pack voltage results in 400 V, a value in the range of levels normally found in current BEVs and slightly below the maximum of 420 V recommended by US Advanced Battery Consortium (USABC) [12]. And secondly, because with this approach an equal distribution of string voltages is achieved, which leads to a simplification of the simulations, since the power sharing is proportional to the size of the battery pack.

C. Drivetrain: motor, inverter and gear

The electric motor nominal power is chosen based on a power ratio criteria. The power ratio of current BEVs is presented in Table IV. Data comes again from publicly available sources. Taking these values into account a power ratio of 100 W/kg is used for the simulated BEV. This is a high value, close to the power ratio of the BMW i3 or the Tesla Model S. Then, considering the DOE technical target [15] of the traction drive system specific power for 2015, 1170 W/kg, the weight of the drivetrain, i.e. motor and inverter, is estimated to 185 kg.

The simulated motor is a scaled version of the one provided by the QSS library from [13] with a maximum torque of 539 Nm and a nominal power of 216 kW @ 5157 rpm, 400 Nm. The torque curve versus speed, as well as its efficiency map can be seen in Fig. 6. Taking into account the motor's maximum speed of 1400 rad/s and a wheel radius of 0.32 m, a gear ratio of 8.06 was used to achieve a top speed of 200 km/h (a similar value achieved by Tesla S).

IV. Energy Consumption Analysis

A. EPA Test Procedures for Electric Vehicles

Automakers in the US market are required to conduct Environmental Protection Agency (EPA) fuel economy test and to display their results among other information in an official label on all new vehicles. Energy consumption is calculated based on standard experimental tests on a dynamometer.

The Electric Vehicle EPA test procedure is described in [14] and summarized in followings:

- **City Test Procedure Summary -** Following SAE J1634 Recommended Practice, the battery is fully charged and then the BEV is driven over successive city cycles until the battery becomes discharged. Then, battery is recharged from a normal AC source and the energy consumption of the vehicle is determined in kWh/mile or kWh/100 miles. The city cycle is the standard FTP-75, which simulates an urban area in the United States.
- **Highway Test Procedure Summary -** The same test SAE J1634 procedure outlined above, is used to determine the highway energy consumption and the highway driving range (except the vehicle is operated over successive highway cycles). In this case, the adopted cycle is the HWFET, that simulates a highway driving.
- In order to compute the annual energy costs EPA adopts as a standard a total driving distance per year of 15000 mi, with 55 % city driving and 45 % highway driving, and an electricity price of 0.12 $/kWh.

Fig. 5: AAUDI prototype. Views of the engine compartment: original Audi A8 4.2 Quattro (second), empty (third) and after conversion into AAUDI (forth).

TABLE III: Li-Ion battery packs and cells employed in current BEVs

Vehicle Model	Pack maker	Cell maker	Chemistry Anode/ Cathode	Cell capacity [Ah]	Cell type	Pack energy [kWh]	Pack voltage [V]	Pack weight [kg]	Cell specific energy [Wh/kg]	Pack specific energy [Wh/kg]	Cell weight fraction [%]
Tesla Model S	Tesla	Panasonic	G/NCA	3.1	Cylindrical	60/ 85	352/ 402	510/ 600	248/ 248	118/ 142	47/ 57
Mitsubishi i-MiEV	LEJ	LEJ	G/LMO-NMC	50	Prismatic	16	330	200	109	80	73
Fiat 500	Bosch	Samsung	G/NMC-LMO	64	Prismatic	24	364	272	132	88	67
Nissan Leaf	Nissan	AESC	G/LMO-NCA	33	Pouch	24	345	294	155	82	53
Smart electric drive	Deutsche Accum.	Li-Tec	G/NMC	52	Pouch	18	340	175	152	103	68
Proposed BEV	-	Kokam	G/NMC	53	Pouch	21/85	400	196/ 589	163	107	65

TABLE IV: Power ratio and energy consumption for commercial and proposed BEVs

Vehicle model	Curb Weight [kg]	Electric Motor nominal power [kW]	Vehicle power Ratio [W/kg]	Battery pack size [kWh]	Combined energy consumption [kWh/100mi]	Cost to drive 25 miles [$]	Annual electricity cost [$]
BMW i3 (full electric)	1195	130	109	22	27	0.81	500
Nissan Leaf 2013	1520	80	53	24	29	0.87	500
Mitsubishi i-MiEV	1080	47	44	16	30	0.9	550
Ford Focus Electric	1674	92	55	23	32	0.96	600
Smart electric drive	958	55	57	17.6	32	0.96	600
Novel BEV (FP)	1581	216	137	21	33	0.96	600
Novel BEV (FP in city, FP + SP in highway)	1581/2170	216	100/137	21/85	35	1.05	650
Tesla Model S 60 kWh	2025	225	111	60	35	1.05	650
Tesla Model S 85 kWh	2108	270	128	85	38	1.14	700
Novel BEV (FP + SP)	2170	216	100	85	40	1.2	700
Mercedes-Benz B-Class Electric Drive	1785	100	56	36	40	1.2	700
Toyota RAV4 EV	1830	115	63	41.8	44	1.32	850

For the purpose of fair comparison an equivalent test procedure is followed in this paper. The proposed novel BEV concept is modelled and its performance simulated over the predefined city and highway driving cycles. After running the simulations, the losses caused by the charger are assumed to be constant and equal to 93 %, which is the US Department of Energy (DOE) technical target for 2015 [15].

B. Simulation Results

Since the business model of the battery swapping stations is not considered, no advanced energy management or balancing strategies were applied during the simulation procedure. In that sense, both packs are fully charged at the beginning of the test and the same efficiency was considered for the DC/DC converters. In order to ensure the same discharge rate in both packs, it was considered a DC/DC converter for the FP when the SP is installed.

Fig. 7 presents the voltage and current profiles for each string of battery cells, during the city and highway driving cycles. It can be observed the voltage decreasing according to the pack's discharge and an increase of the current, once the mass during each test is the same and each cycle iteration demands the same power profile. Fig. 6 shows the torque versus EM speed points of both tests. From these results, it can be seen that during the FTP-75 cycle the majority of the electric motor's operating points have energy efficiency lower than 80%. In contrast, during the HWFET cycle, the electric motor operates in an higher velocity range, with higher energy efficiency than the FTP-75's operating points.

It can be observed that, considering only the FP (Fig. 7a) the currents are higher, when compared to the case of the combined pack (Fig. 7b), despite being less demanding in terms of power peaks. Although the first case presents a lower mass and lower power peaks (Fig. 6), the fact of presenting only one string of cells demands higher currents, increasing internal losses. Furthermore, the EM was designed to support the combined pack. Therefore, for a smaller pack and lower speeds, the EM will actuate in lower efficient areas (see Fig. 6). On the other hand, the speed and torque demands are higher in HWFET driving cycle, but the presence of a bigger

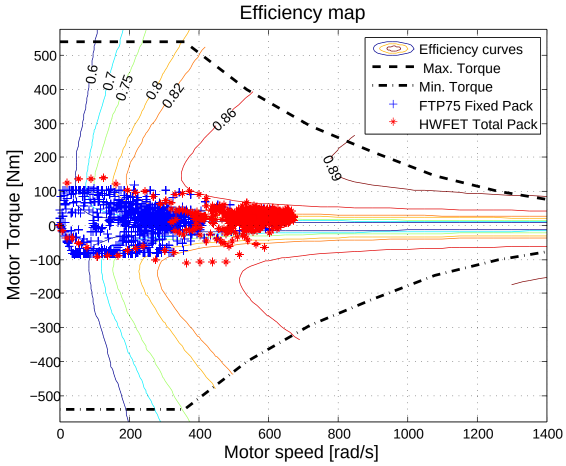
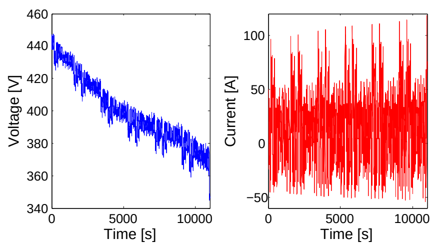
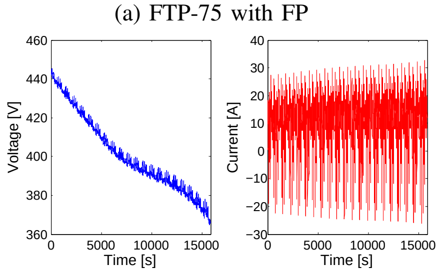


Fig. 6: Efficiency Map with Torque vs. Speed from FTP-75 with fixed pack and HWFET with FP+SP.



(a) FTP-75 with FP



(b) HWFET with FP+SP

Fig. 7: Voltage and Current Profile

pack reduces the current demands on each string. It should also be noted that, in general, the mass of the proposed solution with only the FP is higher than the mass of other commercial BEVs with similar pack size, since the virtual platform and electric powertrain are oversized to withstand the load of the SP. For these reasons, the city energy consumption results for the proposed solution should be slightly higher when compared to other vehicles with similar pack size. Moreover, the highway energy consumption results for the proposed concept are expected slightly higher when compared to Tesla Model S 85 kWh, due to a slightly higher vehicle mass and aerodynamic coefficient. As shown in Fig. 8, the energy consumption simulations results are consistent with these assumptions.

Nevertheless, neither commercial BEVs with a 20 kWh single pack have the ability to run longer cycles, e.g. Ford

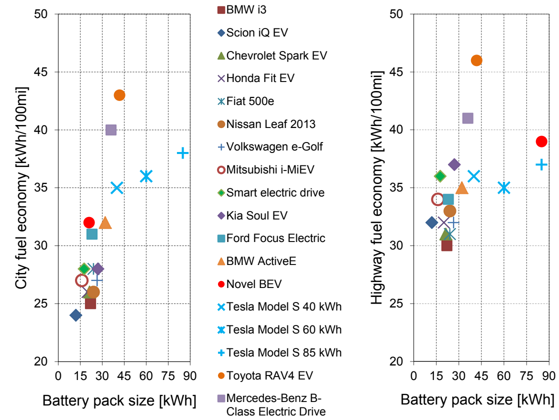


Fig. 8: City and highway energy consumption as a function of battery pack size.

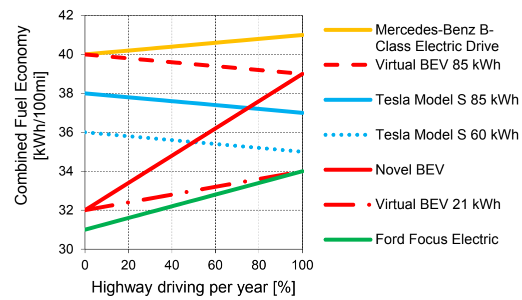


Fig. 9: Combined energy consumption calculated as a function of the percentage highway driving per year.

Focus Electric, nor commercial BEVs with a $>$ 40 kWh single pack, e.g. Mercedes, Tesla or Toyota, can present low consumes such the proposed solution during small/urban cycles (see Fig. 9).

V. Life Estimation

Uncertainty in the lifetime of the direct-owned fixed LIB pack generates uncertainty in the techno-economic analysis. Hence, the impact on battery lifetime of the novel BEV concept in comparison with a conventional topology is evaluated in this section.

The purpose is to support the following techno-economic analysis and not to build a performance model. This means that the target is only to predict when the end of life (EOL) criteria will be achieved, in order to include, if necessary, battery replacement costs in the analysis.

In addition, it should be noted that LIB manufacturer's datasheets provide very limited information about lifetime. For the Kokam cell considered in this study, the only information provided by the manufacturer is that the cell can carry >1500 cycles under cycling conditions of 100 % DOD, 1 C-rate cycling and $23 \pm 3°\mathrm{C}$ and 2000 cycles at 80 % DOD.

Hence, it is difficult to predict the battery lifetime, especially in e-mobility applications, due to complex characteristics of charging/discharging profiles.

To better evaluate the lifetime, two distinct LIB post-processing models are considered. These off-line models are built around the idea of incremental loss of lifetime due to charging/discharging conditions, i.e. use or cycle ageing instead of time or calendar ageing.

Obviously, the same driving profiles and conditions described for the following techno-economic analysis are considered here. This corresponds to the standards defined by EPA for the purposes of energy consumption and annual fuel cost estimation [14].

A. Ah/Wh-throughput model

The only stress factor considered in this approach is charging/discharging energy process, i.e. Ah/Wh-throughput. The model is a modified version from the well-known Ah/Wh-throughput models presented in [16], [17]. Results show a linear relationship between capacity fade and Ah-processed.

Therefore, the annual energy processed while driving E_{drv} and charging E_{cha} the BEV is expressed as

$$E_{drv} = \sum_{\zeta} E^{*}_{drv,\zeta} D_{\zeta}, \quad \zeta \in \{city, highway\} \tag{12}$$

$$E_{cha} = \frac{E_{drv}}{\eta_{cha}} \tag{13}$$

where $E^{*}_{drv,\zeta}$ are energies processed per mile (kWh/mi) in city and highway driving calculated according to EPA test procedures, D_{ζ} are city and highway driving distances per year (mi) according to EPA standards, and η_{cha} is battery charging efficiency of 99 %.

Then the average computed battery lifetime in years, N_y, can be calculated as

$$N_y = \frac{Q_u r_{EOL}}{\alpha_{drv} E_{drv} + \alpha_{cha} E_{cha}} \tag{14}$$

where Q_u is the usable energy capacity of the battery pack at the beginning of life (BOL), which corresponds to 19.3 kWh according to the simulations presented in a previous section, r_{EOL} is the EOL criterion, which corresponds to 20 % capacity fade, i.e. $r_{EOL} = 0.2$, α_{drv} and α_{cha} are the relative driving and charging energy capacity fade coefficients, which are estimated in [16], [17] for experimental data from cycle life tests conducted on A123 LiFePO4 LIB cells under real driving conditions.

B. Cycle counting model

The only stress factor considered in this approach is DOD or cycle depth. The model is a modified version of the cycle counting model presented in [16], [18]. Results show an exponential relationship between number of cycles and DOD. This model may be extended using a rainflow cycle counting method as shown in [19], but for sack of simplicity this approach is not followed here. Model is parametrized based on data from charging/discharging tests at constant C-rate.

The average DOD is calculated as

$$DOD = \sum_{\zeta} \frac{F_{\zeta} R_{\zeta}}{Q_{\zeta} \eta_{\zeta}}, \quad \zeta \in \{city, highway\} \tag{15}$$

where F_{ζ} is the percentage of city or highway travelled, calculated according to EPA test procedures, R_{ζ} is the driving range for city and highway cycles, η_{ζ} is the fuel efficiencies (mi/kWh), and Q_{ζ} are the energy capacity of the battery packs at the BOL, which corresponds to 21.18 kWh and 84.72 kWh, respectively.

Then, the total number of cycles N_{cycles} before EOL are estimated using the next exponential equation:

$$N_{cycles} = a \times DOD^{b} \tag{16}$$

where a = 1570 and b = -1.22 are parameters estimated by curve fitting using aforementioned information provided by the manufacturer of the Kokam cell.

C. Results

Using the Ah/Wh-throughput model, the battery lifetime for both the 21 kWh and the 85 kWh is estimated $>$ 15 years. On the other hand, using the cycle counting model, the battery lifetime for both the 21 kWh and the 85 kWh is estimated $>$ 1600 cycles, which corresponds to driving $>$ 150000 mi. Therefore, in both cases, estimated lifetime is above the standard useful life of a car defined by EPA of 150000mi/15 years [14]. Hence, according to the lifetime models, the impact of the novel BEV topology proposed on battery lifetime is negligible.

VI. Economic Analysis

Assessing the cost-effectiveness is complex. Many factors influence the total cost of ownership (TCO), including (but not limited to) base selling price of the vehicle, incentives, taxes, form of payment, financial resources, driving patterns, cost and availability of swapping spots, energy costs, battery degradation and battery replacement cost and criteria, residual cost of the vehicle and battery at EOL, etc.

For the sack of simplicity, it is assumed that no tax credits or other purchase incentives are available, neither any form of a delayed payment, a loan or a similar financial arrangement. For same reason, residual cost of the vehicle and battery at EOL, insurance rates and tire and maintenance costs are dismissed. Battery degradation and battery replacement are neglected based on the lifetime analysis of Section V. Energy costs and energy consumption are estimated in Section IV. An annual growth of electricity price is considered according to official forecasts of the US Energy Information Administration [15]. Other assumptions are explained in followings.

A. Base Selling Price

The US base selling price before incentives is estimated based on public available data of manufacturer's suggested retail price (MSRP) from current BEVs in the market. Note that the MSRP does not include taxes, license or registrations fees. Two scenarios are considered (see Fig. 10). In the first one the price is obtained using a linear regression from data of MSRPs of Tesla Model S (40 kWh, 65 kWh, 85 kWh). In the second one the price is obtained using a non-linear logarithmic regression from data of MSRPs of all the commercial BEVs listed in Fig. 8 except Tesla Model S.

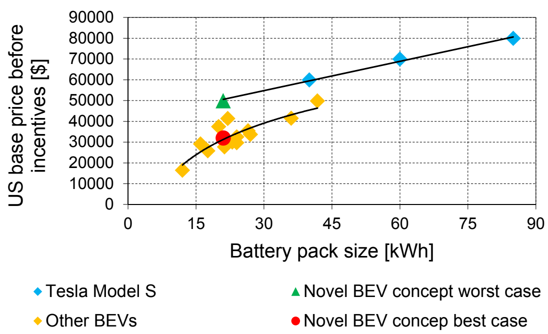


Fig. 10: Base selling price as a function of battery pack size.

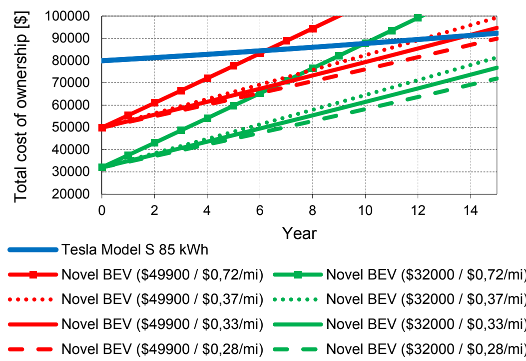


Fig. 11: Total cost of ownership.

B. *Cost and availability of swapping*

In [20] the economic and utility of a BEV battery swapping service plan is compared to traditional direct ownership options. Across the wide range of variables considered in [20] to estimate cost-of-service, the cost and size of batteries, cost of financing, and the battery swap-spot utilization rate are the most sensitive factors. Regarding the battery, three different cost coefficients are considered according to DOE technical targets [15], and three different battery sizes are considered (18.6 kWh, 28.8 kWh, 40.0 kWh) resulting from three different range scenarios (50 mi, 75 mi, 100 mi).

In this paper a larger swappable battery pack is proposed (64 kWh). In favour of the proposed concept, a larger pack would result in higher battery-swap-spot utilization rate, due to the lower average number of range extensions needed. However, at the same time, a larger battery pack would result in higher cost of batteries. Weighting both factors, it is possible to estimate the monthly service fee for the proposed concept from the results shown in [20]. Although, in contrast to [20], only a low-service, low-cost class swap-spot infrastructure is considered here. Low-service class means that higher time spent per swap is expected. However, due to the low number of swaps per year, this is not considered a key factor for consumer satisfaction. Low-cost class means that the cost of the swapping-station is considered on the lower bounds. This is not a strong assumption, since as explained above swap-spot cost is not a sensitive factor. Moreover, higher battery-swap-spot utilization rate leads to lower cost of swap-spots.

Based on these assumptions, using the approach described in [20] and considering two different battery cost scenarios defined as DOE technical targets for 2015 and 2022 [15], 187.5 US$/kWh and 450 US$/kWh, the monthly service fee of battery swapping per customer is estimated as US$ 185 and US$ 405, respectively. This monthly fee leads to a cost of swapping of 0.33 US$/mi and 0.72 US$/mi, respectively, according to the defined driving patterns.

It should be noted that, as opposed to [20], electricity costs are not included in the monthly fee, and are evaluated later based on driving patterns. As well, cost of private chargers is neglected, since an on-board charger is considered and its cost included in the base selling price.

C. *Total cost of ownership*

Based in previous assumptions the TCO is calculated for the proposed BEV and compared with a Tesla Model S 85 kWh, which is nowadays the only commercial vehicle with such a large pack (see Fig. 11). As aforementioned, two base selling price scenarios (US$ 49900, US$ 32000) and two swapping costs scenarios (0.33 US$/mi, 0.72 US$/mi) are considered.

It should be noted that a perfect range extension is considered. This means that a range extension event starts with both the fixed and swappable battery fully charged and finishes with both batteries fully discharged, and that a battery swap spot is always available at this point in time and space. Moreover, it is assumed that the single pack vehicle is operating under a non-swappable model and the additional cost of fast charging, if any, is not considered (only energy costs are computed).

It can be seen in Fig. 11 that considering the best selling price and the worst swapping cost scenario, the TCO of the proposed BEV does not exceed the TCO of the Tesla Model S 85kWh until year 10 or 150000 mi driven. If the worst selling price scenario is chosen the TCO lines intersect before year 7 or 105000 mi drive. On the other hand, whenever the best swapping cost scenario is considered, TCO of proposed BEV does not meet the TCO of the Tesla until year 14 or above.

Dotted and dashed lines are plotted in Fig. 11, corresponding to the TCO calculated based on a US$60-80 cost per swap predicted by Tesla[2], equivalent to an estimated cost per mile of 0.28-0.37 US$/mi. Considering this swap-cost window economic benefits are always observed.

VII. CONCLUSION

In this paper, the energy consumption performance and cost-effectiveness of a novel BEV concept based on a small fixed (21 kWh) and a big swappable LIB pack (64 kWh) are evaluated in comparison with direct owned not swappable single pack BEVs. The evaluation process included the stages: (1) modelling proposed BEV according to certain vehicle design assumptions, (2) defining drive patterns or test procedures, (3)

[2]Rogowssky M., "Tesla 90-second battery swap tech coming this year," *Forbes*, June 21, 2013. Available: http://www.forbes.com/sites/markrogowsky/2013/06/21/tesla-90-second-battery-swap-tech-coming-this-year [Retrieved 15.12.2014]

evaluating energy consumption in simulations, (4) estimating the impact of the proposed concept on battery lifetime, (5) estimating the base selling price of the proposed BEV, (6) calculating the cost of swapping service and (7) evaluating the economics based on a TCO analysis.

Regarding the impact of the proposed BEV concept on battery degradation, an Ah/Wh-throughput model and a cycle counting model are used to estimate the battery lifetime. These models only consider certain stress factors, i.e. charging/discharging energy processed and DOD or cycle depth, respectively. Results show a negligible impact. However, this consideration must be taken cautiously due to complex characteristics of ageing phenomena and limited stress factors taken into account. The base selling price of the proposed BEV is estimated based on linear and non-linear regression from public available data of MSRP from current BEVs in the market. Base selling prices of US$ 49900 and US$ 32000 are estimated as worst and best case scenarios.

With the assumed electricity costs, absence of taxes, licenses, registration fees, insurances, maintenance costs and purchase incentives, the TCO is calculated for the proposed BEV concept and compared with a Tesla Model S, which is nowadays the only commercial vehicle with such a large battery pack (85 kWh). Economic benefits are observed over the single pack not-swappable BEV concept whenever the 0.33 US$/mi swap-cost is computed. If the 0.72 US$/mi swap-cost is considered economic benefits are only observed if the lowest base selling price of US$ 32000 is considered.

In general, it can be stated that there is always an economic benefit if either swap-cost or base selling price are kept in a moderate window. Moreover, the proposed BEV concept removes without additional costs other concern associated with direct owned single pack swappable topologies, how to get the original pack after a swapping event. Further benefits include improved city energy consumption (up to 20 %).

Due the obtained results, further studies involving energy management issues should be taken in consideration, such the ones already studied by the authors [19], [21]. From the customer perspective is expected that the FP to be more protected relatively to the SP. Also, the running costs are not the same for each pack. Therefore, the energy consumption of the fixed pack should be smaller to reduce degradation and to maximize energy of it at the end of the driving pattern. On the other hand, a lower energy consumption of the SP leads to lower running costs, since it is expected that some fee be applied to the SP. This trade-off could be explored in order to maximize the FP+SP properties and a proper sensitivity analysis could provide the economical boundaries of this proposed strategy. Future extension of this paper may include comparison with direct owned swappable BEV and conventional ICE too.

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